EFFECTS OF LAND USE ON THE HYDROLOGY OF DRAINED COASTAL PLAIN WATERSHEDS

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ABSTRACT

Some of the world's most productive cropland requires artificial or improved drainage for efficient agricultural production. Soil hydraulic properties, such as hydraulic conductivity and drainable porosity, are conventionally used in design of drainage systems. While it is recognized that these soil properties vary over a relatively wide range within a given soil series, it is generally assumed they can be approximated based on soil type, independent of crop or land use. Effects of land use on hydrology of drained soils in the North Carolina lower coastal plain were investigated by comparing hydrologic measurements on drained agricultural cropland, drained forest land (Loblolly pine), and an undrained forested wetland. Higher ET on the drained pine forest site resulted in reduced drainage outflow and deeper water tables compared to the agricultural site. Measurements for the one year of record available for the wetland site showed water tables near the surface but outflows similar to the drained forest site. Field effective hydraulic conductivity in the top 70 cm of the drained forest site was more than two orders of magnitude greater than that of corresponding layers of the agricultural site. Drainable porosity, based on measured soil water characteristics, was also much higher for the forested site. Long term (50-year) DRAINMOD simulations predicted average annual drainage outflow of 51.4 cm for the agricultural field as compared to 37.6 cm for the forested site. The difference resulted primarily from greater ET predicted for the forested site. Because of the high conductivity of the surface layers, predicted surface runoff from the forested site was nil as compared to an average annual runoff of 13 cm for the drained cropland site. Results of long-term simulations were used to analyze these effects for the widely variable seasonal and annual weather conditions of eastern NC.

1. INTRODUCTION

A large percentage of cropland along the Atlantic and Gulf coasts of the United States requires improved drainage for efficient agricultural production. About 40% of North Carolina's cropland has been drained. Much of this land is in the lower coastal plain where drainage systems have been installed to remove excess water during periods of precipitation excess. Intensive drainage systems have also been installed on more than 400,000 ha of plantation forests in the region. Drainage

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systems on both agricultural and forested lands normally consist of parallel open ditches, typically 100 m to 200 m apart and 0.8 to 1.2 m deep. Some agricultural lands are drained with parallel subsurface drain tile or plastic tubing 20 to 50 m apart and 0.9 to 1.2 m deep. This paper examines the effect of land use and drainage system design on the hydrology of drained soils in the North Carolina coastal plain.

Continuous measurements of outflow rates, water table depth and precipitation have been conducted since the mid-1990s on a 10,000 ha watershed in the lower coastal plain near Plymouth, NC. The Tidewater Research Station, which has been the site of numerous drainage and water table management studies, is located within this watershed. Data from the watershed study and from previous studies on the Tidewater Experiment Station are used herein to analyze the effects of land use on hydrology.

2. WATERSHED STUDY

A watershed study was initiated in 1995 to determine the cumulative impacts of land use and management practices on hydrology and water quality of a poorly drained, lower coastal plain watershed. A 10,000 ha watershed, located near Plymouth, in eastern North Carolina, was instrumented to measure drainage rates, water table depths, meteorological variables, and to sample for water quality on both field and watershed scales (Chescheir et al., 1998). In addition to measuring the hydrology and water quality for the various land uses and management practices on the watershed, our object was to develop watershed scale simulation models to predict cumulative

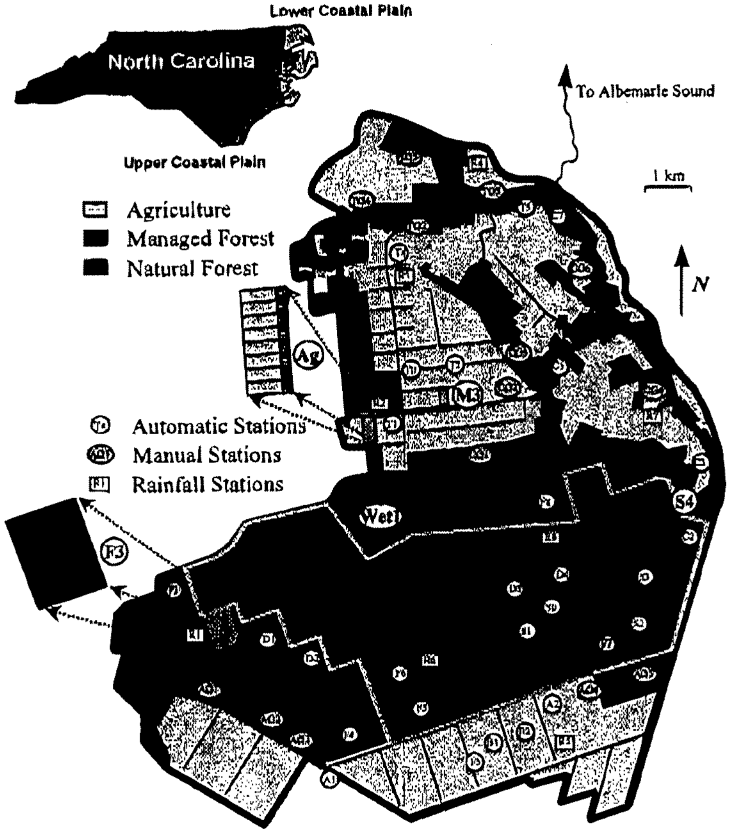

Figure 1. Schematic of the Kendircks Creek Watershed near Plymouth, NC, showing fields Ag 3 and F3 and the wetland, W1.

impacts over the long term. A range of models of different complexities was developed. (Fernandez et al., 2001, 2002, 2003, 2004; Amatya et al., 2001, 2004). A summary of the capabilities and input requirements of the models was given by Skaggs et al. (2003). These watershed models are based on the water management model DRAINMOD for quantifying the field hydrology, and use various approaches for handling the hydraulics in the drainage channels, the hydrodynamics of nutrient transport, and changes in nutrient concentrations as the drainage water flows from the field edge to the watershed outlet. In this paper we will concentrate on field scale, rather than watershed scale processes. Data from the watershed study will be used to analyze the effect of land use on hydrology and soil properties. The model DRAINMOD will also be used to investigate the effects of land use under the wide range of weather conditions that occur over a long period of climatological record in eastern NC.

A schematic of the 10,000 ha Kendricks Creek watershed showing the land use, location of the main drainage canals and natural streams, gauging stations, and water table recorders is given in Figure 1. Land use on the watershed is typical of the region, consisting of cropland (36%), managed forest (52%), unmanaged forested wetlands and riparian areas (11%). The watershed is relatively flat (surface elevations 3 to 6 m above mean sea level) and the soils are mostly poorly drained and very poorly drained mineral and organic series. The primary drainage system on both agricultural and managed forest lands is a network of ditches and canals which divide the watershed into a mosaic of regularly shaped fields and blocks of fields. Field ditches, spaced 80 to 100 m apart and 0.6 to 1.5 m deep, provide both surface and subsurface drainage to most of the agricultural and forest land. They drain to a network of collector and main canals which lead to the watershed outlet. Some of the unmanaged forested lands do not have ditches and some of the agricultural lands, especially that on the Tidewater Research Station (located in the northwest part of the watershed and draining to station T4) have subsurface drains (tile and plastic) at various spacings and depths. Flow measurements were recorded and drainage waters sampled for water quality analyses at 54 stations within the watershed. These stations are located at the outlet of the watershed, at the outlet of sub-watersheds, on main drainage canals, and at the outlet of agricultural and forested fields. Water table depth was recorded continuously at 28 locations and precipitation at 8 sites on the watershed. A detailed description of the watershed and instrumentation is given by Chescheir et al. (1998). An 8-year data set has been collected on the site and measurements continue.

Measured results from three fields and one sub-watershed will be analyzed in this paper to determine the effect of land use on hydrology. Long-term simulation results for a fourth field (M3) will be used to demonstrate differences that can occur within the same land use and soil series. The fields are denoted in Figure 1 as Ag3 (agriculture), F3 (forest), and Wet1(wetland). The soils for all three fields are classified as Cape Fear sandy loam (Typic Umbraquults, clayey, mixed, thermic), or Portsmouth sandy loam(Typic Umbraquults, fine loamy, mixed, thermic). Both soil series are very poorly drained, nearly level soils formed on alluvial sediments on stream terraces. The Cape Fear has more clay and a lower hydraulic conductivity in the B horizon than the Portsmouth. Otherwise the soils are quite similar. Sandy lenses starting at depths of 1 to 1.5 m typically underlie both series. The distribution of soil types on the watershed is shown in Figure 2.

The drainage system for Ag3 consists of parallel 10 cm diameter corrugated plastic drains buried 1.2 m deep and 23 m apart. This field has been part of a drainage water management study since 1990. The drainage system design, instrumentation to measure drainage rates and water table depths, crop history and soil properties were recently documented by Youssef (2003) and Youssef et al. (2004). The soil on Ag3 is primarily Portsmouth s.l. A corn-wheat-soybean (3 crops in 2 years) rotation is grown on the site. The drainage and data collection system for F3 was documented by Diggs (2004) and by Shelby (2002). The drainage system consists of parallel open ditches about 1 m deep and 85 m apart. The soil is Cape Fear s.l. and the vegetation was 15 year old Lobolly pine at the time of data collection. Drainage for the wetland site (Wet1) occurs through shallow (<0.4 m deep) widely spaced natural drains that meander through the site. Chescheir et al., (1998) described experimental procedures and results of hydrologic studies on the site. All three sites were instrumented to continuously measure water table depths and drainage rates. Rainfall was recorded with both tipping bucket and manual gauges at 8 locations on the watershed.

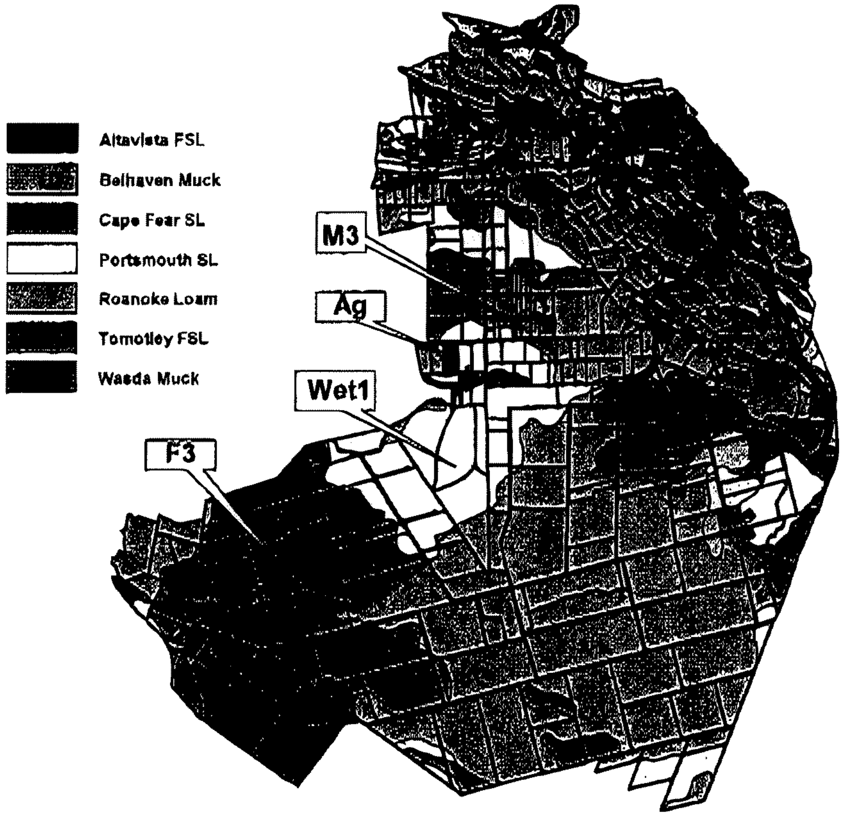

Figure 2. Distribution of soil series on the Kendricks Creek watershed.

3. Water Table Depth.

An example of the effect of land use on water table depth is shown in Figure 3 where measured water table depth is plotted for a two-year period (1994-1995) for three sites, all located within a 3-km radius, and all on the very poorly drained Cape Fear and Portsmouth soil series. Site Wet1 is an undrained forested wetland; site F3, a drained (parallel drainage ditches 0.9 m deep and 85 m apart) 15-year old pine plantation; and site Ag3, a drained agricultural field (10-cm diameter subsurface drains, 1.1 m deep and 23 m apart). Drainage intensity (DI) is inversely proportional to the square of the drain spacing, so, based on the drainage system parameters, DI for the agricultural site should be about 14 times greater than that for the managed forested site. However, it is clear from Figure 3 that the water table on the forested site is, on average, much deeper and recedes more rapidly than for the agricultural site. The most obvious reason for the difference is evapotranspiration (ET). Rooting depths are deeper, and the ET demand continues on a 12-month basis without interruption for the pine forest, compared to agricultural crops, which are planted and harvested one or two times per year. ET caused the water table to be drawn down to a depth of more than 2 m for the managed forest, as compared to a maximum depth of about 1.4 m for the agricultural site.

In addition to ET, there are also substantial differences in the soil properties, which may significantly affect the hydrology. Measured drainage rates and water table responses indicate that drained forested soils have field effective hydraulic conductivities (K) that are greater than those for agricultural lands on the same soil series. This is indicated in Figure 3 by the drawdown rates when the water tables in both forested and agricultural sites were near the surface during a period of low ET in February 1995. Even though the drain spacing in the forested site was nearly four times that of the agricultural site, the drawdown rate was about the same. The larger pores that apparently cause higher K also result in higher drainable porosities in forested than in agricultural lands, where the soils are frequently tilled. As a result water table fluctuations in the drained agricultural cropland (Ag3) are more frequent and the rise in response to rainfall is greater than for either the drained forest or the wetland forest sites. Surface runoff usually occurs on these poorly drained soils when the water table rises to the surface such that the profile is essentially saturated.

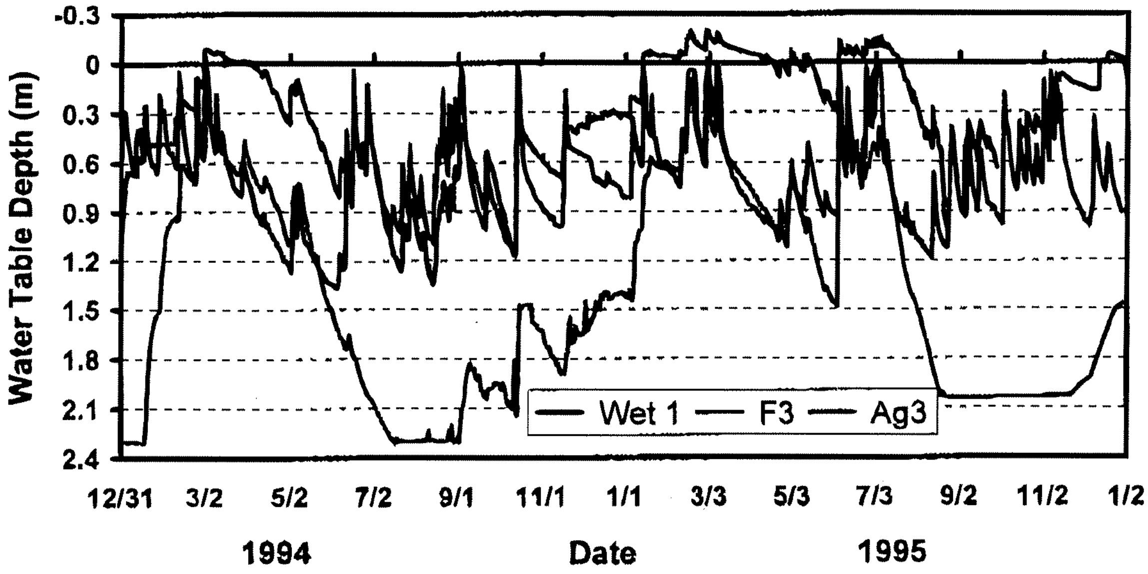

Figure 3. Water table fluctuations over a two-year period for a forested wetland site (Wet 1), a drained forested (Loblolly Pine) site (F3), and a drained agricultural site (Ag3).

This occurred far more frequently on the agricultural site than on the drained forested site (Figure 1). Due to both greater ET and hydraulic conductivity, surface runoff rarely occurred from the drained forested lands in our study. In contrast, the water table in the wetland forest, which had only shallow (<0.5 m deep), widely spaced natural drains, was at or above the surface during extended periods of time. Soil properties on this site are similar to those on the managed forest, but, without drains, there is no outlet for surface and subsurface water so the water table is naturally closer to the surface.

4. Annual Drainage Outflow

The effect of land use on annual drainage outflow is shown in Figure 4 for 1996 and 1997. This period was chosen because 1996 was the last year of flow data collection for the wetland site and the first year of flow data for the forested site (F3). However, the period does represent a relatively wet year (1996) and a relatively dry year (1997). Average precipitation at the Tidewater Research Station is 1287 mm. We received 1436 mm (112% of normal) in 1996 and 1072mm (83% of normal) in 1997. Flow measurements did not begin on F3 until February 22, 1996, so comparison of cumulative flows was initiated at that date. There were problems with the F3 record for 1997 so data for that year were not plotted. Cumulative outflow for the 3000 ha forested S4 watershed (Figure 1) is plotted for comparison (The S4 watershed is primarily plantation pine with field drainage systems similar to F3). Subsurface drainage was measured for the Ag3 plot, but not surface runoff. The water table rose to the surface and surface runoff occurred several times during 1996. The amount of surface runoff was predicted by DRAINMOD (calibrated for the plot) and added to the measured subsurface drainage to get the total outflow plotted in Figure 4. Total surface runoff was predicted to be 23.9 cm in 1996. Measurements of outflow from the wetland (Wet1), the drained forested site (F3) and the forested watershed (S4) included both surface runoff and subsurface drainage. However there was no surface runoff, neither observed nor indicated by measured water table elevations, from the drained forested sites in 1996. Nor was there indication of surface runoff from any of the drained sites, including Ag3, in 1997.

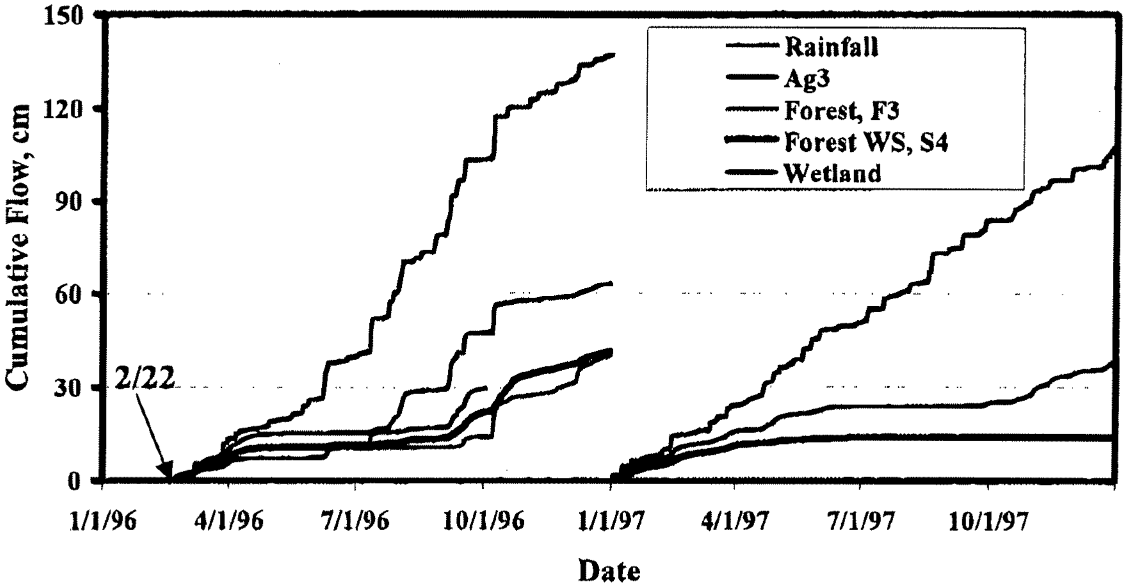

Figure 4. Cumulative drainage for a forested wetland site, a drained forested site (F3), an agricultural site (Ag3), and a 3000 ha drained forested watershed (S4).

The cumulative drainage relationships for Wet1, F3 and S4 were very similar in 1996. Cumulative outflow from the wetland (Wet1), F3 and S4 were very similar in 1996. Outflow from the wetland was somewhat greater than from the drained forests (F3 and S4) early in the year. This was probably because of differences in the soil water status at the end of 1995 (Figure 3). The water table was 1.5 m deep on F3 compared to being right at the surface on Wet1 at the beginning of 1996. Thus precipitation early in the year would have resulted in immediate flow from the wetland, which was saturated, while flow from the drained forest was delayed as water was stored in the profile, raising the water table. Measurements on the wetland site were discontinued on October 1. Total drainage depths from F3 and S4 were 40 and 41 cm as compared to 63 cm from the Ag3 site for the period 2/22 through 12/31, 1996. The 22 cm difference in drainage is assumed to be mostly due to greater ET from the forested fields, which have both deeper rooting system and greater leaf area than the winter wheat (harvested in June) and soybean (planted in June, harvested in Nov.) on Ag3. An approximate water balance, including accounting for a small difference in soil water storage, indicates that ET for the 10.2 month period was about 760 mm from Ag3 compared to 970 mm for F3.

There was a larger difference in outflow for the relatively dry 1997. Outflow from the Ag3 site (planted to corn April 15, harvested September) was 38 cm as compared to 14 cm from the S4 watershed. Again the difference (24 cm) is primarily due to greater ET from the forested watershed, which had about 930 mm of ET compared to 690 mm from Ag3.

5. SOIL PROPERTIES

One of the most striking effects of land use on the hydrology of drained is the impact on soil properties. This issue was discussed briefly with regard to the differences in water table depths between forested and agricultural lands (Figure 3). Impacts of these differences on cumulative and annual outflows are not as obvious, but years of experience in measuring soil properties of poorly drained coastal plain soils has led to the conclusion that hydraulic conductivity and drainable porosity are nearly always substantially larger on forested than on agricultural lands. This difference is very important in the application of simulation models to predict hydrology and water quality on both field and watershed scales. Conventional application of models nearly always assigns soil property values based on soil series, without regard to the effect of surface cover on those properties. There is a reasonably good understanding and acceptance of the variability of soil properties within a soil series due to subtle differences in structure, texture, and organic matter. However, the effect of land use or vegetation is rarely considered. This can lead to serious errors if land use has a significant effect on the soil properties.

Field effective values of hydraulic conductivity, K_e, were determined for Ag3 and F3 from continuously measured drainage rates and water table elevations. K_e was estimated from the Hooghoudt equation (van der Ploeg et al., 1999), which may be written as,

$$q = 4K_e\, m\, (m + 2\, d_e)/ L^2 \tag{1}$$

where, referring to Figure 5, q is drainage rate (cm/day), K_e is equivalent hydraulic conductivity below the water table (cm/day), m is midpoint water table elevation above the drains (cm), de is the equivalent depth from the drain to the restrictive layer (cm), and L is the drain spacing (cm).

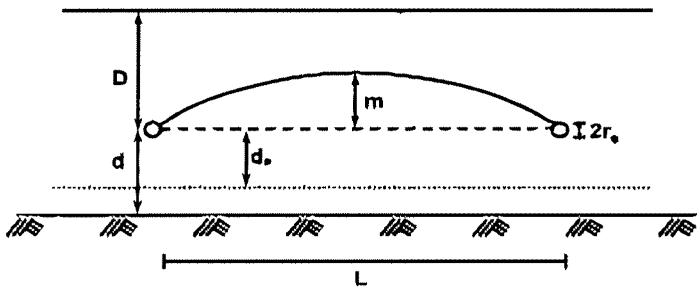

Figure 5. Schematic of water table position for steady state drainage; used herein to define Drainage Intensity, DI

The equivalent depth from the drain to the impermeable layer, de, can be calculated in terms of the actual depth, d, drain spacing, L, and the effective drain radius by equations developed by Moody (1967) or by van der Molen and Wesseling (1991). K_e can then be determined from measured values of q and m by solving equation 1.

Use of this method to estimate K_e assumes that steady state conditions exist and that ET is negligible. While conditions in the field are rarely, if ever, steady, the Hooghoudt has been found to perform satisfactorily for conditions when the water table is moving slowly, such that the unsaturated zone above the water table is approximately "drained to equilibrium" with the water table. We determined K_e for Ag3 and F3 by plotting measured q versus m for winter months when ET is low. Results are shown in Figure 6. The quantity m was defined as shown in Figure 5 for the AG3 site, which has subsurface drains at a depth of 1.2 m. Drains for the F3 forested site were open ditches with a V-notched weir in the outlet. Depth from average ground surface to the bottom of the V (the water level in the ditch) was 0.7 m. In this case, m was defined as the elevation of the midpoint water table, as referenced to the water level in the ditch. K_e was calculated from equation 1 for the whole range of water table elevations and associated q values. Nearly all field soils are made up of layers or horizons with different values of K, so the effective K_e values varied with water table elevation. The K values for individual layers were determined from the following equation for the equivalent K for parallel flow through a layered profile.

$$K_e(d_1+d_2+d_3+\ldots) = K_1d_1+K_2d_2+K_3d_3+\ldots \tag{2}$$

where, K_1 is the hydraulic conductivity and d_1 is the thickness of the first layer below the water table, K_2 and d_2 are the respective values for the second layer, etc. The K values for the individual layers were determined by starting with small m values such that the only K value active was that of the bottom layer. Then the value of the layer at the next highest elevation was determined, and the process repeated until the K values of all the layers of the profile were estimated.

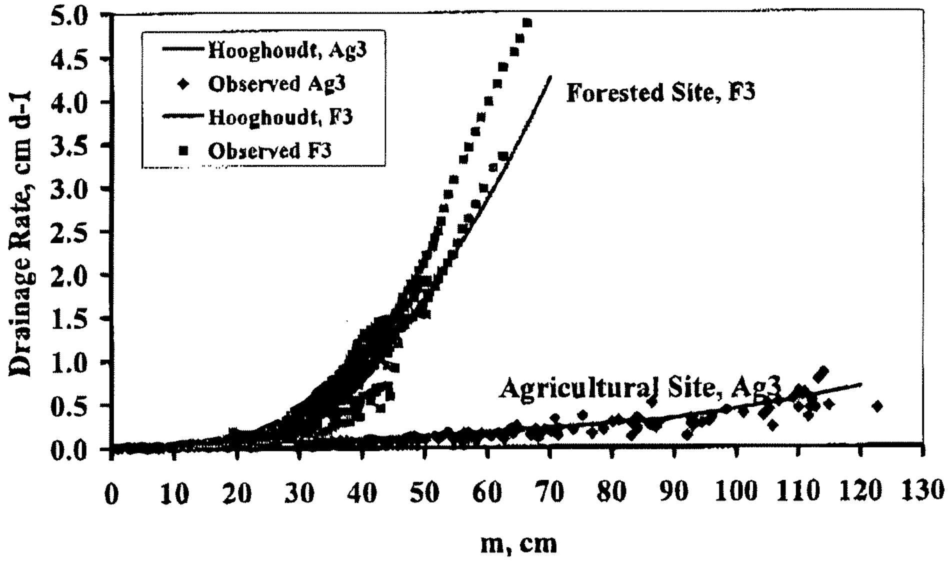

Figure 6. Measured drainage rates plotted as a function of measured midpoint water table elevations, m for the agricultural site, Ag3, and the forested site, F3.

The substantial difference in hydraulic conductivity between the Ag3 and F3 sites is obvious from Figure 6. For example the drainage rate from F3 for an m value of 40 cm was about 2 cm/d compared to about 0.1 cm/d from the Ag3 site. The Ag3 site has a 23 m drain spacing, so, other factors being equal it should have a much higher flow rate than the F3 site with an 85 m ditch spacing. Hydraulic conductivity (K) values by layer, as determined from the data in Figure 6, are given in Table 1 for both sites. The solid curves in Figure 6 are the relationships predicted by the Hooghoudt equation using the K values in Table 1. According to the soil series description, the Portsmouth soil of Ag3 should have a higher K value for the B horizon (depths of 30 to about 90 cm) than the Cape Fear soil of F3. However, the field effective K values from the forested site F3, as determined by the methods described above, were over two orders of magnitude greater than those of Ag3 for depths down to 70 cm (Table 1). These differences have a profound effect on drainage rates as shown in Figure 6. Low flow rates (and therefore low K values) for the Ag1 site could have been partially caused by large head losses near the 10-cm drain. This could have caused the effective K values for the layer between depths of 100 to 235 cm to be lower than would have occurred with open ditch drains. Nevertheless, the major reason for the big difference in K values between the two sites (Table 1) is the very large field effective hydraulic conductivity for F3, not the relatively low values for Ag3.

Table 1. Summary of soil properties for sites Ag3 and F3.

Agricultural Site, Ag3		**Forest Site, F3**	
Depth, cm	**K, cm/hr**	**Depth, cm**	**K, cm/hr**
0-30	3.8	0-30	1000
30-80	1.3	30-40	850
80-100	0.54	40-50	500
100-240	0.44	50-70	40
		70-240	5

Water Table Depth, cm	**Drainable Porosity, % Ag3**	**F3**
25	1.5	22.5
50	4.4	15
75	5.3	9
100	7.4	3
150	8.4	2

The very rapid K values in F3 are apparently due to large interconnected pores and well structured soil conditions that develop under forest conditions. These large pores empty under small soil water tensions causing the drainable porosity to also be high. This is shown in Figure 7, which plots the depth of water drained as the water table falls from the surface to depths up to 200 cm. These curves were calculated from the soil water characteristics (pF curves) measured for the different soil horizons for each site. The results indicate that to lower the water table from the surface to a depth of 100 cm about 4 cm of water would have to be removed for the Ag3 site, while about 15 cm would have to be drained for the F3 site. The drainable porosity may be defined as the slope of the relationships given in Figure 7. For example, the drainable porosity corresponding to a water table depth of 50 cm is 4.4% for the Ag3 soil compared to 15% for F3 (Table 1). These data again emphasize the extreme difference in soil properties between these two common land uses in eastern NC.

6. HYDROLOGIC SIMULATIONS

DRAINMOD (Skaggs, 1978, 1999) was used with the soil properties given in Table 1 and Figure 7 to simulate the hydrology of Ag3 and F3. Details of additional inputs are given by Youssef et al.(2004) and Diggs (2004) for the Ag3 and F3 sites, respectively. Simulations were conducted for the 50-year period (1951-2000) using weather data for Plymouth, NC. Results are summarized in Figure 8. In spite of the fact that hydraulic conductivity and drainage rates are higher for the forested F3 site, average annual outflow (subsurface drainage + surface runoff (RO)) was greater for

Ag3 (51.4 cm) than for F3 (37.6 cm). This is due to higher ET predicted for the deep-rooted pine on F3 as discussed previously regarding differences in water table depths. Average annual ET predicted for F3 was 91.2 cm compared to 77.3 cm for Ag3 (Figure 8). Another big difference in the hydrology is surface runoff. The water table rarely rose close to the surface in F3. Furthermore, the field was bedded when the pine trees were planted, creating a surface topography that would store as much as 10 cm of water before RO could begin. This surface storage, which was active only during very high rainfall events, plus the high K and rapid drainage in the upper part of the profile, resulted in negligible RO predicted for F3 for the entire 50-year period. By contrast, average annual RO for the agricultural field, Ag3, was 13.2 cm.

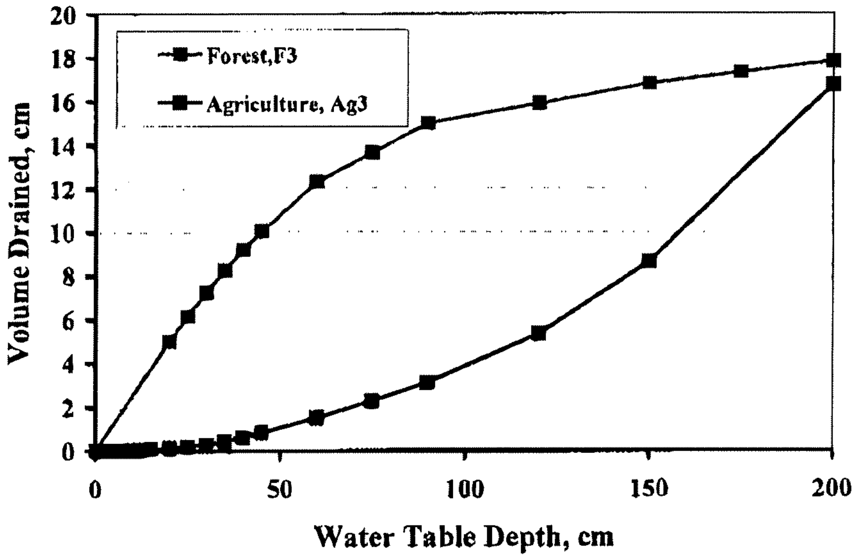

Figure 7. Relationship between volume of water drained (per unit surface area) and water table depth. The volume (or depth) drained is the amount of water that would have to be removed to lower the water table from the surface to the depth on the abscissa.

Average monthly outflows for the 50-year period are plotted in Figure 9 for the two sites. Average predicted outflows from Ag3 were higher than from F3 for all months. Differences were largest for summer months when potential ET is high and the deeper rooted pine trees remove more water than corn and soybean. Differences during February-April were small because PET is low and ET is limited more by atmospheric factors than by vegetation. That is, ET was not often limited by water availability to the vegetation, either forest or agricultural crops, during this period. PET is also low in November and December when there were differences between outflows from Ag3 and F3. These differences occurred because of the carry-over effect of dry soil conditions in the summer and fall. In years with dry periods in late summer and fall, the trees dried out the profile to much deeper depths than did agricultural crops (Figure 3). Drainage in December and January in those years began earlier from Ag3 than from F3. It was not uncommon to have no drainage from F3 in those months. The water table depth was not as great going into the winter and drainage began earlier and was greater from Ag3 than from F3.

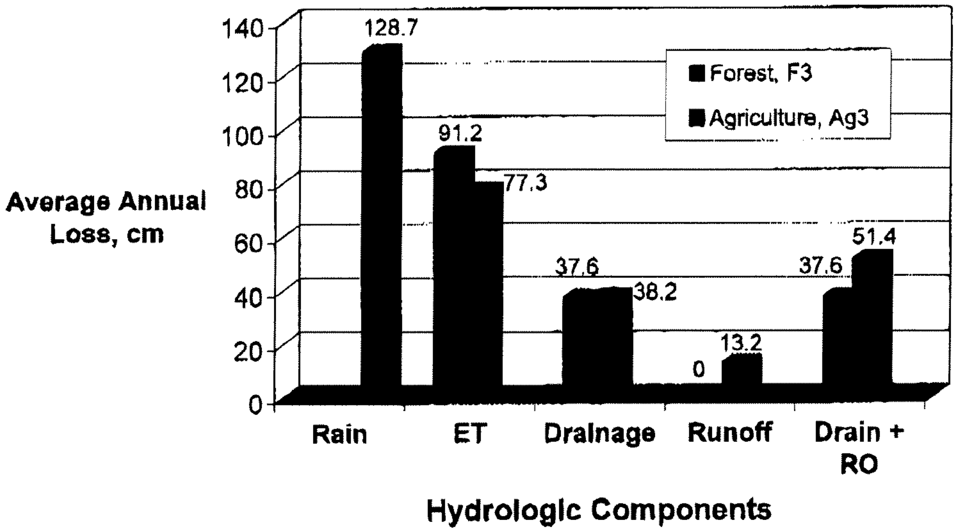

Figure 8. A summary of average annual values predicted for hydrologic components in 50-year simulations for the agricultural site, Ag3, and the forested site, F3.

Frequency distributions of predicted annual outflow are plotted in Figure 10 for forested and agricultural sites. Predicted outflows ranged from 5.8 to 67.7 cm for F3 and from 22.4 to 81.9 for Ag3. Similar distributions for the monthly flows are plotted in Figure 11 for January and June. These results show that flow was predicted for January of every year for Ag3 and in 96% of the years for F3. For June, however, flow was predicted in only 38% of the years for the forested site, F3, versus 58% of the years for the agricultural site, Ag3.

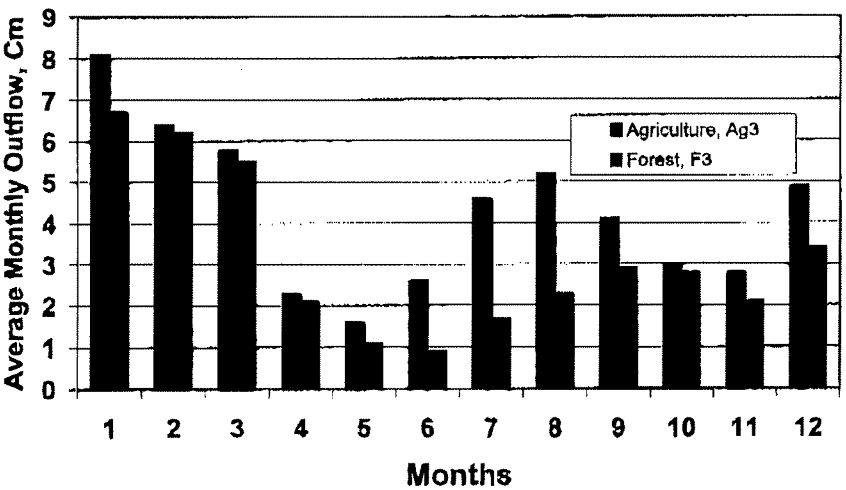

Figure 9. Average of monthly predicted outflows (subsurface drainage +RO) for Ag3 and F3.

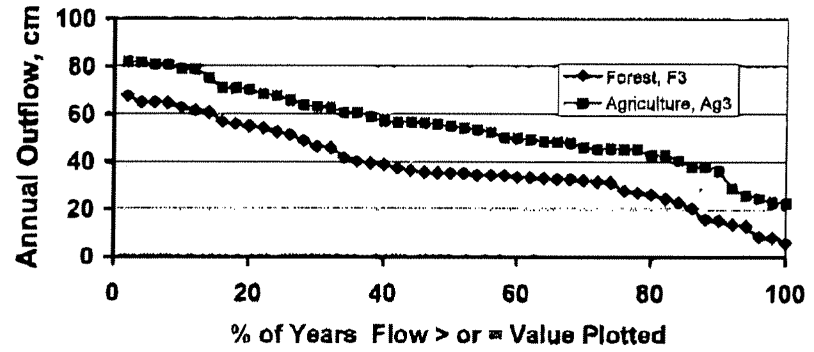

Figure 10. Frequency of predicted annual outflows (subsurface drainage + surface RO) for the forested and agricultural sites.

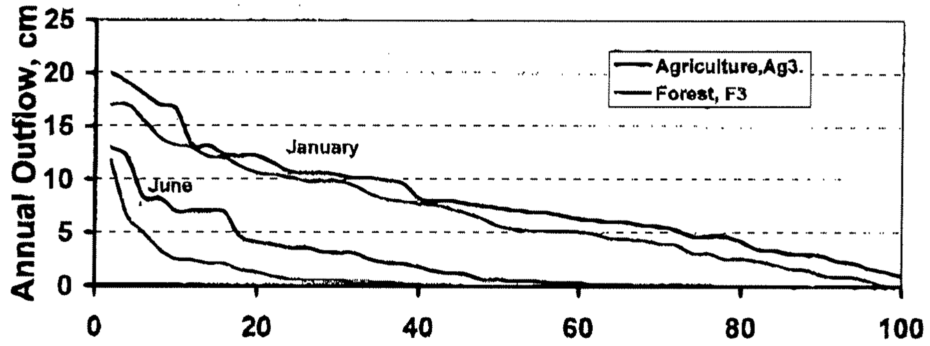

Figure 11. Frequency of predicted January and June outflows (subsurface drainage + surface RO) for forested and agricultural sites.

7. SUMMARY AND CONCLUSIONS

Effects of land use on the hydrology of drained soils in the North Carolina lower coastal plain were investigated by comparing hydrologic measurements on drained agricultural cropland, drained forest land (Loblolly pine), and an undrained forested wetland. Higher ET on the drained pine forest site resulted in reduced drainage outflow and deeper water tables compared to the agricultural site. Measurements for the one year of record available for the wetland site showed water tables frequently near the surface, but outflows similar to the drained forest site. Results of this study support the conclusion that hydraulic conductivity and drainable porosity for the top meter of the profile are substantially greater for forested than for agricultural fields. Field effective hydraulic conductivity in the top 70 cm of the drained forest site was more than two orders of magnitude greater than that of corresponding layers of the agricultural site. Drainable porosity, based on measured soil water characteristics, was also much higher than the forested site when the water table was within 75 cm of the surface. Long term (50-year) DRAINMOD simulations predicted average annual drainage outflow of 51.4 cm for the drained agricultural field as compared to 37.6 cm for the forested site. The difference resulted primarily from greater ET predicted for the forested site. Because of the high conductivity of the surface layers, predicted surface runoff from the forested site was nil, compared to an average annual runoff of 13 cm for the drained cropland site.

REFERENCES

Amatya, D.M., G.M Chescheir, G.P. Fernandez, RW Skaggs, and J.W. Gilliam. (2003). "Methods for estimating nitrogen transport in poorly drained watersheds", Trans ASAE, in review.

Amatya, D.M., G.M. Chescheir, G.P. Fernandez, R.W. Skaggs, and J.W. Gilliam. (2001). "An Export Coefficient Based Water Quality Model Linked with @RISK Tool. In ASAE Paper 01-2213, pp.31-34, ASAE, St. Joseph, MI.

Chescheir, G.M., D.M. Amatya, G.P. Fernandez, R.W. Skaggs, and J.W. Gilliam. (1998). "Monitoring and modeling the hydrology and water quality of a lower coastal plain watershed". Proc. of the 1998 WEF Conference, Denver, CO, May, 1998, pp.215-222.

Diggs, J. (2004). SIMULATION OF HYDROLOGY AND NITROGEN LOADING FROM FORESTED FIELDS IN EASTERN NC. M.S. Thesis, Department of Biological and Agricultural Engineering, N.C. State University, Raleigh.

Fernandez, G.P., R.W.Skaggs , G.M. Chescheir, and D.M. Amatya. (2001). "WATMOD: An integrated watershed scale hydrology and water quality model". ASAE P. 012082, St. Joe, MI.

Fernandez, G.P., R.W. Skaggs, G.M. Chescheir and D.M. Amatya. (2002). "WATGIS: A GIS-Based Lumped Parameter Water Quality Model", *Transactions of ASAE.* Vol 45(3), pp.593-600.

Fernandez, G.P., G.M. Chescheir, R.W. Skaggs and D.M. Amatya. (2003). APPLICATIONS OF A DRAINMOD-BASED MODEL TO A LOWER COASTAL PLAINS WATERSHED. Presented at 2003 Internatioal Meeting, Las Vegas, NV, ASAE Paper No. 032167, St. Joseph, MI.

Fernandez, G.P., R.W.Skaggs , G.M. Chescheir, and D.M. Amatya. (2004). MODELS FOR PREDICTING HYDROLOGY AND NITROGEN LOSSES FROM POORLY DRAINED WATERSHEDS. Trans ASAE, in review.

Moody, W.T. (1967). "Nonlinear differential equation of drain spacing". J. Irrig. and drainage Div., ASCE, 92(IR2), pp.1-9.

Shelby, J.D. (2002). EVALUATION OF HYDROLOGY AND WATER QUALITY IN A LARGE WATERSHED IN NORTH CAROLINA'S LOWER COASTAL PLAIN FOLLOWING THE HURRICANES AND RELATED STORMS OF 1999. M.S. Thesis, Dept. Biological and Agricultural Engineering, N.C. State University, Raleigh. 144p

Skaggs, R.W. (1978). A WATER MANAGEMENT MODEL FOR SHALLOW WATER TABLE SOILS. Report 134, Water Resources Research Institute of the University of North Carolina, N.C. State University, Raleigh. 178p.

Skaggs, R.W. (1999a). "Drainage simulation models". P 469-500 In R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural Drainage, SSSA, Madison WI.

Skaggs, R.W., G.M. Chescheir, G. Fernandez and D.M. Amatya. (2003). "Watershed models for predicting nitrogen loads from artificially drained lands". Proceedings of the Conference, Total Maximum Daily Load, Environmental Regulations II, Albuquerque, NM, Nov. 8-12. ASAE, St. Joseph, MI, pp. 442-452.

Van der Ploeg, R.R., R. Horton and D. Kirkham. (1999). "Steady flow to drains and wells". P213-264 In R.W. Skaggs and J. van Schilfgaarde (ed.) Agricultural Drainage, SSSA, Madison WI.

van der Molen, W.H. and J. Wesseling. (1991). "A solution in closed formand a series solution to replace the tables for thickness of the equivalent layer in Hooghoudt's drain spacing formula". Agricultural Water Management.19, pp.1-16.

Youssef, M. Y. (2003). MODELING NITROGEN TRANSPORT AND TRANSFORMATIONS IN HIGH WATER TABLE SOILS. PhD Dissertation, N.C. State University, Raleigh, 270 p.

Youssef, M.Y., Skaggs, R.W., G.M. Chescheir, and J.W. Gilliam. (2004b). THE NITROGEN SIMULATION MODEL, DRAINMOD-N II: 2. MODEL PARAMETERIZATION AND FIELD TESTING. Water Resour. Res. (submitted)